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FLUCTUATING SURFACE PRESSURE MEASUREMENTS ON USB WING

USING TWO TYPES OF TRANSDUCERS

By

James B. Reed
Boeing Commercial Airplane Co.

and

James A. Schoenster
Langley Research Center

October 1975

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16. Abstract

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ABSTRACT

Measurements of the fluctuating pressures on the wing surface of an upper-surface-blown powered-lift model and a JT15 engine were obtained using two types of pressure transducers. Description of the pressures measured is made using overall-fluctuating pressures and power spectral density analyses for various thrust settings and two jet impingement angles. Comparison of the data from the two transducers indicate that similar results are obtained in the lower frequency ranges for both transducers. The data also indicated, that for this configuration the highest pressure levels occur at frequencies below 2000 Hz.

SUMMARY

One of the current concepts being developed for short takeoff and landing (STOL) aircraft uses the exhaust of the engine impinging directly on the upper-surface of the wing. A current program for this upper-surface-blown (USB) powered-lift concept will use full-scale model data to compare with small-scale model data. One of the parameters being evaluated is the fluctuating pressures on the surface of the wing. Because two different types of transducers are being used in this program, a test was conducted in which data from each of these types of transducers were compared. One of the transducers is a large (2.54 cm diameter) condenser microphone, the other a miniature (0.318 cm diameter) pressure transducer. Data on the surface pressures were obtained to determine the general levels and shape of the power spectrum to be expected from this configuration and to compare the measurements from the two types of transducers. Results of these measurements are presented in overall fluctuating pressure levels, 1/3-octave spectrum levels and narrowband spectrum levels for varying thrust levels and two angles of jet impingement.

INTRODUCTION

Current powered-lift configurations being developed for short takeoff and landing (STOL) aircraft require flow attachment of the engine exhaust gases on the wing surface. Measurements of the surface fluctuating pressures caused by this attachment are of considerable interest, since potentially they are sources of noise generation, vibration, and structural loading. Previous studies measuring surface pressure fluctuations, such as references 1 and 2, indicate that transducer size and installation technique can cause considerable difficulty in obtaining reliable data. Although the referenced studies investigated supersonic boundary layers, whereas the boundary layers for the powered-lift systems are generally subsonic, some doubt remained as to the ability to compare data using different types of transducers for the subsonic case. Wing-surface transducer installation presents size and mounting problems and, in addition, the transducer environment in powered-lift aircraft requires the systems to withstand high temperatures and vibration. A current program for upper-surface-blown (USB) powered-lift aircraft in which data from a full-scale ground test model and a small-scale ground test model are to be compared, requires the use of different types of pressure transducers. Concern over the ability to compare these data led to a study in which these two different types of pressure transducers were installed in a model of an upper-surface-blown-wing-flap system using a JT15D engine. One of the transducers used was a large (2.54 cm diameter) rugged, water-cooled, solid diaphragm, condenser microphone. The other was a miniature pressure transducer (0.318 cm diameter) with a silicon diaphragm and four active arm Wheatstone bridge balance network.

The purpose of this report is to present and compare the data obtained from these two types of transducers when measuring, simultaneously, the fluctuating pressures on the surface of the wing of an USB system using a JT15D engine. Comparisons of the overall root-mean-square fluctuating pressures (OAFPL), 1/3-octave band surface fluctuating pressure level (SFPL) and narrow-band SFPL are presented.

In addition, using the data from these transducers, some of the characteristics of the measured fluctuating pressures on the surface were investigated. Results from evaluating the effect of measurement location, engine thrust level, and jet attachment angle are presented.

MODEL AND APPARATUS

The outdoor static test apparatus simulated an upper surface blowing (USB) vehicle with the engine-nozzle, wing-flap arrangement illustrated in figure 1. The engine used was the United Aircraft of Canada JT15D-1 turbofan. This engine has a bypass ratio of 3.3:1 and a fan pressure ratio of 1.53:1. The simulated wing and flap system was of boilerplate fabrication with surface contours similar to those of an airplane to be tested in the Langley full-scale tunnel. The wing could be rotated about the fixed leading-edge position to change the thrust impingement angle, the angle of inclination between the thrust and the wing-chord plane. Details and dimensions of the static test apparatus are given in figure 2.

The entire USB model including the inlet, engine, exhaust nozzles, and wing-flap structure was mounted on a floating frame instrumented to measure both normal and axial forces relative to the engine centerline. Three parts of the model were mounted to the floating frame independently: (1) the inlet was

rigidly mounted to the engine support truss; (2) the engines were mounted on strain gages (at the forward engine mount pivots) which were in turn mounted to the engine support truss; and (3) the wing and flap structures were directly mounted to the floating frame. A rubber seal joined the inlet and the engine fan case and the secondary nozzle exit was positioned so as not to contact the wing-flap structure. This arrangement permitted direct measurement of thrust loads of the engine-nozzle combination independent of the normal and axial loads determined from the floating frame strain gages. The inlet was an airplane inlet with two perforated sheetmetal acoustic rings.

The secondary nozzle was a fixed design intended to provide attached flow on the upper surface of the wing-flap system. The secondary nozzle exit was rectangular in shape with an aspect ratio (width/height) of 6.0, and had a deflector to provide thrust inclination onto the wing upper surface at angles of 5° and 11.4° to the wing-chord plane. The elliptical primary nozzle was mounted inside of the secondary nozzle with its exit about 1.0 fan diameter upstream of the secondary nozzle exit. It had the same exit area as the basic round primary nozzle. Although the JT15D-1 engine was rated at 9790N (2,200 lbs) static thrust at sea level standard conditions, maximum continuous thrust in this series of tests was limited to avoid gas turbine overtemperature problems resulting from the use of unmatched nozzles.

TRANSDUCER SYSTEMS

Two types of transducer systems were used. One of the systems used a Photocon 752A solid diaphragm transducer rated at $\pm$68.9kPa ($\pm$10 psi) mounted in a water-cooled flame shield. The other used a Kulite XCEH-1-125-5D miniature pressure transducer rated at $\pm$ 34.4kPa ($\pm$5 psi). The locations of the

transducers, designated 2, 7, and 8, are shown in figure 3. At each location a Photocon transducer, a Kulite transducer, and a thermocouple were flush mounted with the surface. The two pressure transducers at each location were within 6.35 cm (2.5 inches) of each other. Prior to the start of the test, the Kulite at location 8 was found to be inoperative and was not replaced. In addition to the pressure transducers, accelerometers were mounted at various locations on the wing-flap system to assure that overall vibrational levels of the structure were low.

Photocon transducer systems consist of three primary elements; the transducer, a termination network for use with long data cables, and the Dynagage and associated power supply which is a signal conditioning unit. For this test, three Photocon water-cooled model 752A transducers were installed in transite adapters mounted in the wing to provide both thermal and electrical isolation from the wing section (fig. 3). The cooling system used tap water and dumped the transducer exit water. For water lines, copper tubing and threaded fittings were used, since plastic tubing and construction hose clamps were found to leak during a checkout run. A transducer cooling water flow rate of at least 1.9 L/min (0.5 gpm) was maintained through the test. Each Photocon system had been calibrated by Boeing and this value reaffirmed by a calibration check at Langley. One Dynagage unit was replaced by a spare, otherwise the Photocon systems maintained their sensitivity during the transit. All transducers were calibrated (150 dB at 1000 Hz) as installed using a Photocon PC 125 calibrator box held against the flush installation.

The system was designed to have a flat frequency response over the range of analysis interest, but above 5000 Hz, variation up to $\pm$ 3 percent in response could occur. Correction factors for the response were available for

each 1/3-octave band based on laboratory calibration.

The Kulite transducer system consisted of four elements: a diffused semiconductor strain gage transducer with a silicon diaphragm (XCEH-1-125), a protective screen on the diaphram, a connecting tube between the reference side of the transducer and the wing surface, and a Wheatstone bridge power supply-balance unit. The purpose of the connecting tube was to equalize the static pressure loading on the active and reference side of the diaphragm, thereby canceling out that component of the total pressure. The system was designed to have a flat frequency response down to 20 Hz. The Kulite transducers were calibrated in the laboratory and the calibration was confirmed for the installed transducer using the same procedures as those used with the Photocon transducer.

TEST PROCEDURE

Operations of all systems were initially checked during operation of the engine at idle, half power, and maximum continuous thrust. Data were obtained during operation of the engine at idle, maximum continuous, 75 percent, 50 percent, and 25 percent thrust for impingement angles of 5° and 11.4°. Temperatures on the flap surface were used as indications of thrust condition stability and data were recorded when the temperatures stabilized at a constant value. Engine parameters and effective impingement angle were obtained from calibrations of the test stand system. Data were recorded on magnetic tape at 30 ips and later processed through the Boeing Acoustical Laboratory to obtain 1/3-octave band pressures. Selected measurements were further analyzed in 20 Hz bandwidths for a spectrum of 0 to 10 kHz. Since low frequency fluctuations were of concern in selecting transducer rating,

some measurements were analyzed in even narrower 2 Hz bandwidths from 0 up to 1000 Hz. The 1/3-octave band analysis allowed inclusion of microphone correction factors, but the narrowband analyzer did not.

RESULTS AND DISCUSSION

Surface measured pressures are subject to the fluctuations of the wing attached flow as well as the acoustic pressures resulting from turbomachinery noise and jet exhaust turbulence. To evaluate the measurement characteristics of the transducers, these USB flow phenomena and the possibility of small noise source variations between transducer locations must be considered. The Photocon and Kulite measurements are presented as overall fluctuating pressure levels (OAFPL), as 1/3-octave band surface fluctuating pressure levels (SFPL), and as 20 Hz and 2 Hz constant bandwidth SFPL. The narrow 20 Hz width was used for the full frequency spectrum up to 10,000 Hz, and even narrower, the 2 Hz width was used to expand the view of the frequencies below 1000 Hz of special interest for USB flow effects.

The engine parameters and OAFPL are tabulated in table I and 1/3-octave band SFPL are shown in figures 4 and 5. These data are summarized in Figures 12 and 13 after examination of the narrowband data in figures 6 through 11. In figures 6 and 7, the upstream characteristics of the transducers are seen. In figures 8 and 9 the downstream transducer characteristics are compared and effects of thrust variation seen. Photocon data at positions equal distance downstream of the nozzle are compared in figure 10, and the influence of change in jet impingement angle on the low frequency fluctuations is seen for both transducer types in figure 11.

The comparison of the transducer measurements can be summarized from the OAFPL data of table I and explanations derived from 1/3-octave band spectra in figures 4 and 5. First, the Photocon OAFPL levels are an average of 0.3 dB higher than the Kulite at the downstream position (7) but at upstream position (2), the Photocon levels are an average 1.5 dB higher than the Kulite levels. This difference is seen in figures 4 and 5 to be the same as the difference in peak values in the 1/3-octave band spectra. The upstream position evidences two peaks (100 to 250 Hz and 800 to 1000 Hz) and the downstream position evidences one peak (80 to 200 Hz). The difference of an average 0.5 dB between the two Photocon positions downstream (7 and 8 of fig. 5) is due to the centerline position (8) having its peak at a 1 to 2 dB lower level. The peak at location 8 is at one band higher in frequency than the peak at location 7. The increase in impingement angle from 5° to 11.4° varied OAFPL by an average ± 0.5dB, thus indicating no significant trend with the flow being required to turn more for attachment.

Figures 4 and 5 show that good agreement exists between Photocon and Kulite measurements except for the Kulite reading about 1.5 dB lower at frequencies below 400 Hz at the upstream position. Closer investigation using narrowband analysis also involves consideration of the special characteristics of exhaust noise and attached flow, some of which can be calculated or compared using the engine parameters.

The engine parameters in table I were useful for identifying fan and turbine tones and evaluating exhaust noise variation with jet velocity. The percent thrust values are used to identify the conditions rather than being a calculated parameter. In the narrowband analyses, tonal components below 1000 Hz are identified as being the same frequency as the rotor speeds in

revolutions per second (rev/sec) of the low pressure rotor, N_1, or high pressure rotor, N_2, or multiples of these such as $2N_1$ or $3N_2$.

Above 2000 Hz, tones due to the first fan stage (F) with 28 blades (or last turbine stage (T) with 56 blades) are at frequencies equal to the product of the number of blades times the low pressure rotor speed, N_1. Multiples and sums of these tones also occur such as 2F or F + T.

The presence of such turbomachinery components in figure 6 at frequencies above 2000 Hz, and the expanded view of low frequency noise below 1000 Hz in figure 7 are typical of the additional information provided by narrowband analysis. In this case, the data record was the same as that of figure 4. Judgment of relative influence of spectra components depends on the method of analysis and the criteria involved. The constant percentage bandwidth (1/3-octave band) analysis of figure 4 includes a wider frequency range in the higher bands and, hence, emphasizes the levels of frequencies significant to human perceived annoyance above 1000 Hz. Constant band width analysis of this same data in figure 6 (20 Hz BW) shows that the highest levels at a given frequency besides the turbine tone at 5000 Hz, are in the 100 to 200 Hz range rather than at 800 to 1000 Hz as viewed in figure 4. Expanding the view of frequencies below 1000 Hz by 2 Hz BW analysis in figure 7 shows the same peak noise effects at 80 to 250 Hz; this is not as obvious in figure 6.

The presence of tonal components at N_2 and multiples of N_1 and N_2 are seen in figure 7. Although not distinguishable, the shaft speed N_1 would correspond to the peak frequency of the fluctuating pressures. However, a similar 2 Hz BW analysis in figure 8 of the downstream transducers shows the N_1 fundamental is not significant to the spectrum peak levels. The concern here would have been for influences on the surface pressures other than

the attached flow noise.

The broadband levels at the upstream position are compared using figures 4, 6, and 7 once more. Here the 1.5 dB differences below 400 Hz are most evident in figure 7 at 75 percent and max. power, but frequencies where the Kulite is higher are also apparent in figures 4 and 7 from 500 to 1000 Hz at 50 percent and max. power. It may have been that local flow effects such as temperature and velocity gradients between transducers were a cause. A difference in the transducer response at max. thrust above 5000 Hz which is uncorrected in narrowband is also apparent by comparing figures 4 and 6.

Low frequency flow buffeting below 50 Hz was an initial concern in the measurements, but was not apparent in the low frequency data of figure 8. Both transducers show the fluctuating pressures increase in peak frequency and fluctuating pressure level (SFPL) although a lower rate of increase occurs below the peak frequency than above. The spectral trend close to zero is affected by the analyzer per response as it starts to track.

The difference in SFPL between downstream transducers as engine power is varied is further seen in the full narrowband spectra of figure 9. As power setting is decreased, the Photocon indicates lower broadband levels above 1000 Hz than the Kulite although tonal components are the same level. The difference in microphone response, not applied to narrowband, might be as much as 5 dB. The broadband difference between transducers is 5 to 10 dB from 3 to 5 kHz at idle power.

A narrowband analysis (2 Hz) of the downstream Photocon transducers at locations 7 and 8 show similar spectral shapes (fig. 10). The agreement is actually closer than that of the 1/3-octave band analysis (fig. 5). The reason for this closer agreement between the two locations is not known.

However, the analysis shows the high levels to be concentrated in the frequencies below 200 Hz and indicates a dependence on the thrust level of the engine.

The change in impingement angle shows little change in low frequency signals for either Photocons or Kulites in figure 11. The OASPL values in table I showed no more than 0.5 dB increase or decrease in Photocon signals and no more than 0.7 increase or decrease in Kulite signals.

Maximum temperature was generally measured at the downstream centerline location 8 and varied from 138°C (280°F) at idle to 218°C (425°F) at maximum thrust (fig. 3). The increase in impingement angle did not change the downstream temperatures, locations 7 and 8, but increased the temperature at the upstream location 2, by about 22°C, to 224°C (435°F). A summary of significant temperatures was inset in figure 3.

The difference in spectra shape between the upstream and downstream positions in figure 12 illustrates the axial distribution of noise source locations. Noise sources close to the nozzle may be indicated by the lower frequency and higher frequency SPL peaks of upstream position 2. Downstream at position 7, a single dominant peak at a lower frequency than the peaks for position 2 is the basic spectral characteristic.

The variation of the SFPL and the frequency of these spectral peaks with exhaust velocity is shown in figure 13. Maximum OAFPL levels of 157 dB were measured at the downstream location 7.

Although the upstream and downstream spectra were different, the fluctuating pressures of both the OAFPL and the 1/3-octave peak responses were related to the 1.75 power of the jet exhaust velocity as seen in figures 13a and 13b. The frequency of the individual 1/3-octave pressure peaks

were linearly related to the jet exhaust velocity as shown in figure 13c. The lower frequency pressure peak at the upstream measurement location was always below 315 Hz while the pressure peak of the downstream measurement locations was always below 200 Hz.

CONCLUDING REMARKS

A test was conducted to study the use of two types of transducers for measuring surface fluctuating pressures. Measurements were obtained on the wing surface of an upper-surface-blown powered-lift aircraft model, in which the exhaust of a JT15D engine impinged on the wing-flap as attached flow. The jet exhaust velocities investigated ranged from 89.0 m/sec (292 fps) to 273 m/sec (896 fps) and surface temperatures on the wing reach 218°C (425°F). Two types of transducers were used, one a large (2.54 cm diameter) rugged, water-cooled, solid diaphragm, condenser microphone; the other a small (0.318 cm diameter) silicon diaphragm, four-active-arm Wheatstone bridge pressure transducer. The transducers were mounted in close proximity to each other and measurements from each were compared. Comparisons of the overall fluctuating pressure levels (OAFPL) and both 1/3-octave band analysis and constant narrowband analysis below 3000 Hz generally resulted in agreement well within 1.5 dB. Slightly larger differences in the spectral analysis occurred at the lower exhaust velocities and in the higher frequencies at all exhaust velocities. These differences may be attributed to the separation distance between the transducers or, in the case of the high frequencies of the narrowband analysis, a lack of a transducer-size correction factor.

Methods of surface pressure fluctuations measurement were reinforced by this test since both Photocon and Kulite acoustic transducers gave similar recordings of spectra characterizing USB flow. The pressure at the nozzle exit exhibited two peaks in the frequency spectra while the pressure downstream had only one peak in the frequency spectra. In addition, both peak responses in the spectra at the upstream location occurred at higher frequencies than

that of the single peak at the downstream locations. Although these spectra were different, the fluctuating pressures of both the OAFPL and the 1/3-octave peak responses were related to the 1.75 power of the jet exhaust velocity. The frequency of the individual 1/3-octave pressure peaks were linearly related to the jet exhaust velocity.

The lower frequency pressure peak at the upstream measurement location was always below 315 Hz while the pressure peak of the downstream measurement locations was always below 200 Hz. Over a frequency range of 0 to 1000 Hz, the pressure spectral shape and levels were very similar at the downstream locations; one near a projection of the nozzle edge and the other along the engine centerline. Also, the change of jet angle impingement on the wing from 5° to 11.4° had almost no effect on the pressure spectrum at these locations.

Evidence of low frequency flow buffeting below 30 Hz was absent in the data and indicates transducer ratings may be selected according to the estimated peak jet noise level which in this case was 157 dB, measured at the downstream location.

The transducers exhibited durability and installation effects according to their size. The Photocon transducer is relatively large but is very rugged for continuous test. It requires water-cooling attachments and extra signal conditioning equipment which requires additional balancing. The Kulite unit has the advantage of miniature installations and simple signal balancing methods. Its installation in terms of wire connections is somewhat fragile relative to maintenance of multiple wire and tube connections.

REFERENCES

1. Lewis, Thomas L.; Dods, Jules B., Jr.: Wind-Tunnel Measurements of Surface-Pressure Fluctuations at Mach Numbers of 1.6, 2.0, and 2.5 Using Different Transducers. NASA TN D-7087, October 1972.

2. Hanly, Richard D.: Effects of Transducer Flushness on Fluctuating Surface Pressure Measurements. AIAA 2nd Aero-Acoustics Conference, Hampton, Virginia, March 1975.

TABLE I

RUN NO.	CONDITION NAME	ENGINE THRUST N	ENGINE THRUST lbs.	EXHAUST VELOCITY m/sec	EXHAUST VELOCITY fps	N_2 rpm	N_1 rpm	TRANSDUCER OAFPL dB POSITION 2 PHOTOCON	POSITION 2 KULITE	POSITION 7 PHOTOCON	POSITION 7 KULITE	POSITION 8 PHOTOCON
1002	Idle	894	201	92	302	17400	5200	136.8	135.2	141.3	141.3	141.9
.3	Max	5810	1305	273	896	29500	12300	153.0	151.6	157.6	156.8	156.7
4	75%	3830	860	213	700	27100	10300	149.0	147.5	154.1	153.6	153.7
5	50%	3750	619	179	586	25100	9000	–	145.0	151.1	151.1	150.7
6	25%	1800	404	139	455	22300	7300	–	–	147.6	147.3	147.4
7	Idle	827	186	89	292	17000	5000	–	–	141.1	140.6	141.2
8	Max	5810	1308	264	867	29500	12200	–	–	157.1	156.8	157.2
9	75%	3830	860	205	673	27100	10200	–	–	154.1	154.3	153.4
10	50%	2840	639	174	571	25100	8900	–	–	151.6	151.3	150.9
11	25%	1940	436	139	457	22800	7400	–	–	148.1	–	147.7

Effective Impingement Angle – 5° Run 2-6

11.4° Run 7-11

N_1 Low pressure rotor speed ($\pm$ 10%) 28 Fan blades first stage, 56 turbine blades last stage

N_2 High pressure rotor speed ($\pm$ 10%)

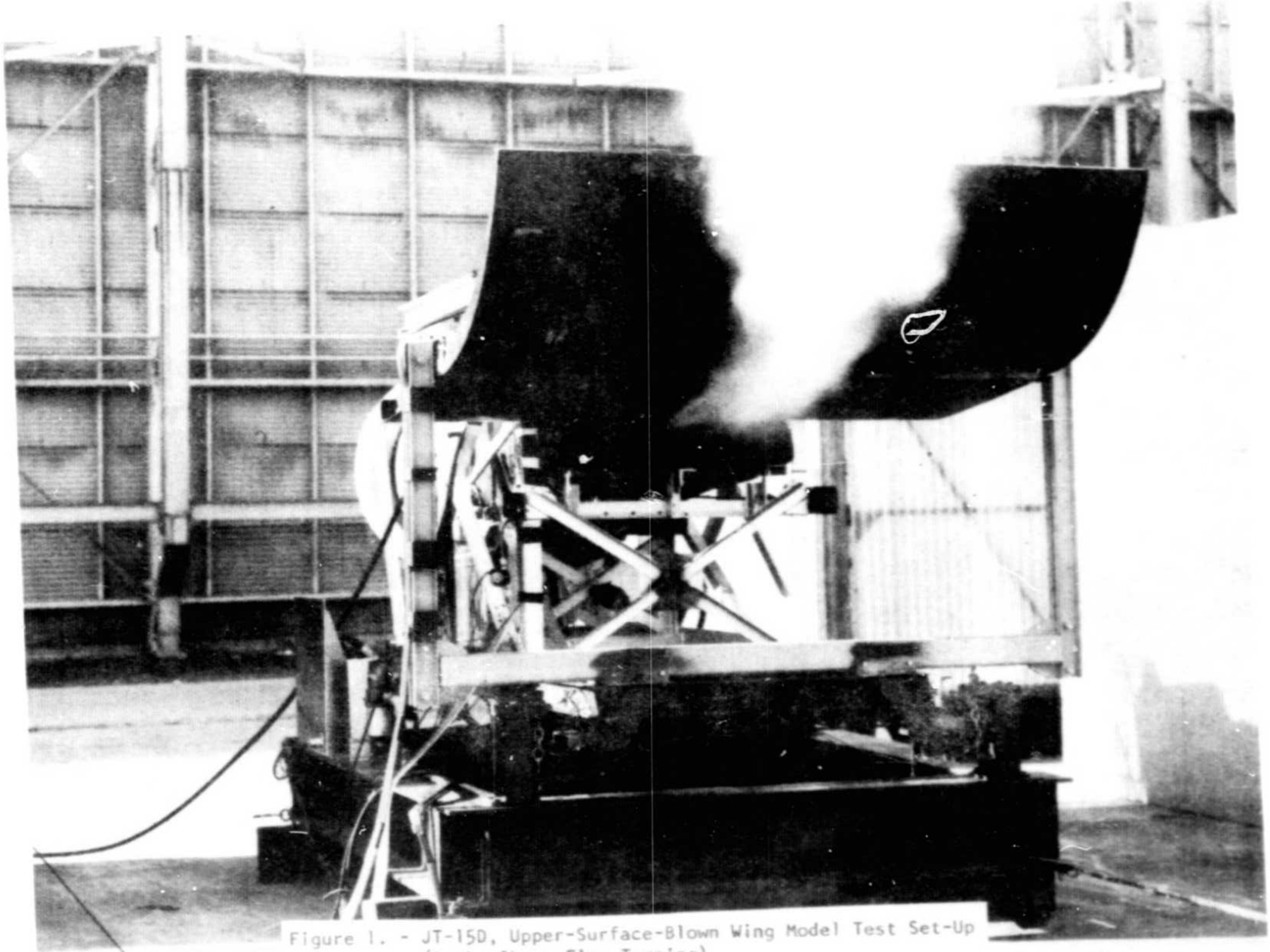


Figure 1. - JT-15D, Upper-Surface-Blown Wing Model Test Set-Up
(Smoke Shows Flow Turning)

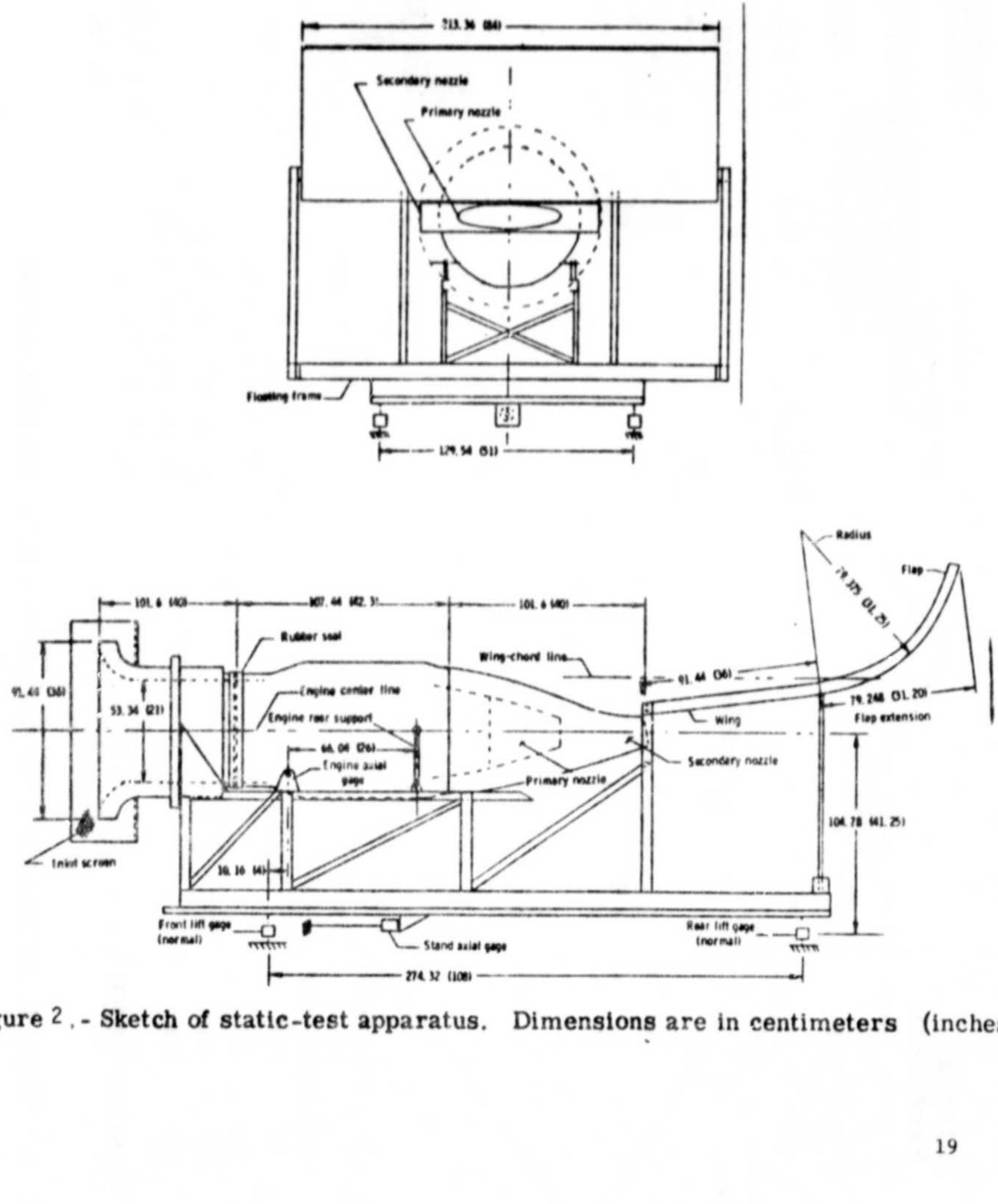
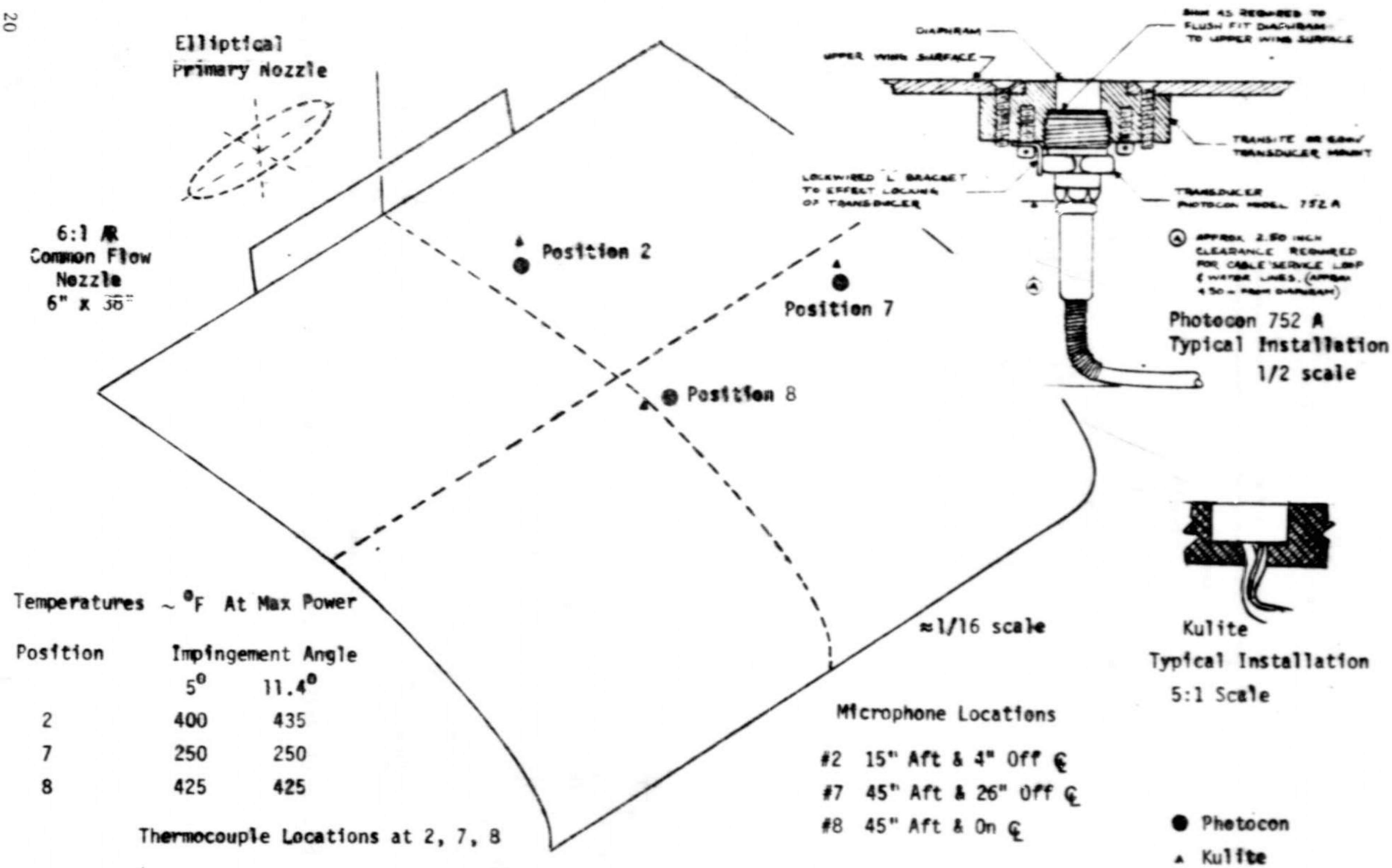


Figure 2 . - Sketch of static-test apparatus. Dimensions are in centimeters (inches).

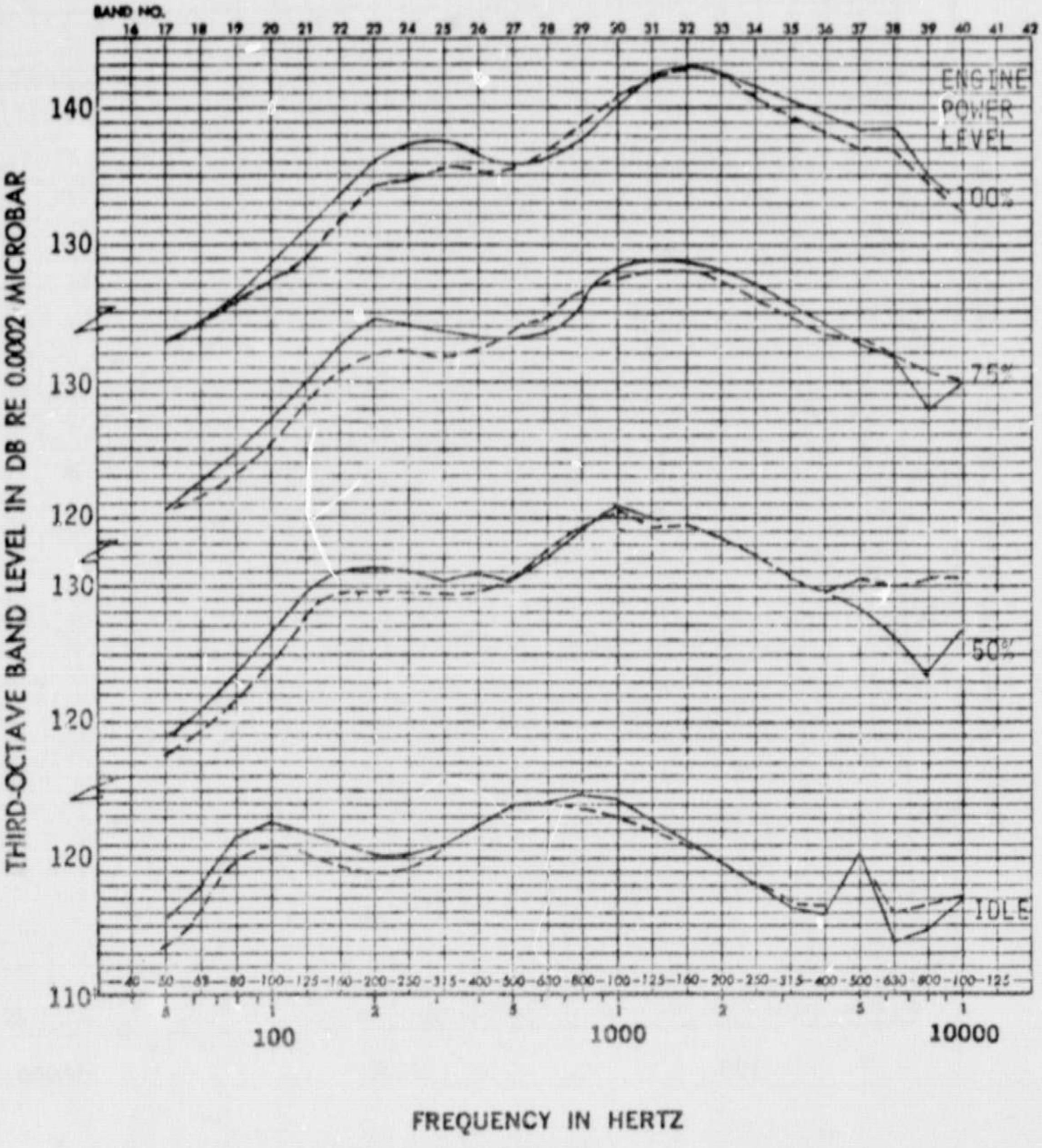


Temperatures ~ °F At Max Power

Position	Impingement Angle 5°	Impingement Angle 11.4°
2	400	435
7	250	250
8	425	425

Thermocouple Locations at 2, 7, 8

FIGURE 3 BOILERPLATE WING AND FLAP SURFACE ACOUSTIC TRANSDUCER LOCATIONS

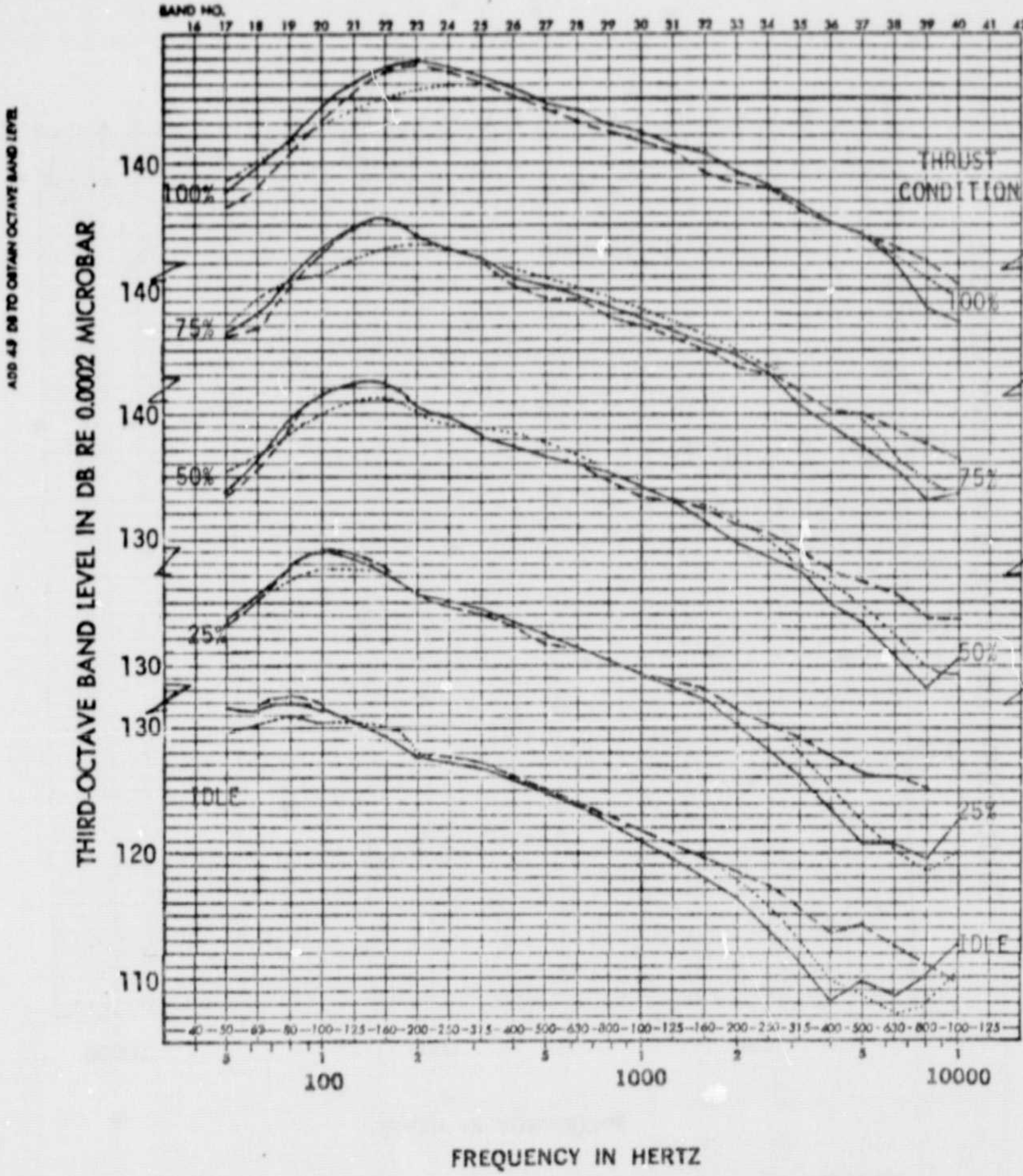


POSITION #2
TRANSDUCER LOCATION
4 IN. OFF Centerline
14 IN. Aft of Nozzle Plane
Tmax = 425°F
Impingement Angle 5°

_______ PHOTOCON
- - - - KULITE

JT15D-1 USB 9-11-74

FIGURE 4 SURFACE PRESSURE FLUCTUATIONS UPSTREAM NEAR NOZZLE



Position #7
Transducer Location
26 IN. OFF Centerline
43 IN. Aft of Nozzle Plane
Tmax = 250°F
——— Photocon
---- Kulite

Position #8
Transducer Location
Centerline
43 IN. Aft of Nozzle
Tmax = 350°F
······ Photocon

FIGURE 5 SURFACE PRESSURE FLUCTUATIONS DOWNSTREAM ON WING NEAR INITIATION OF FLOW TURNING IMPINGEMENT

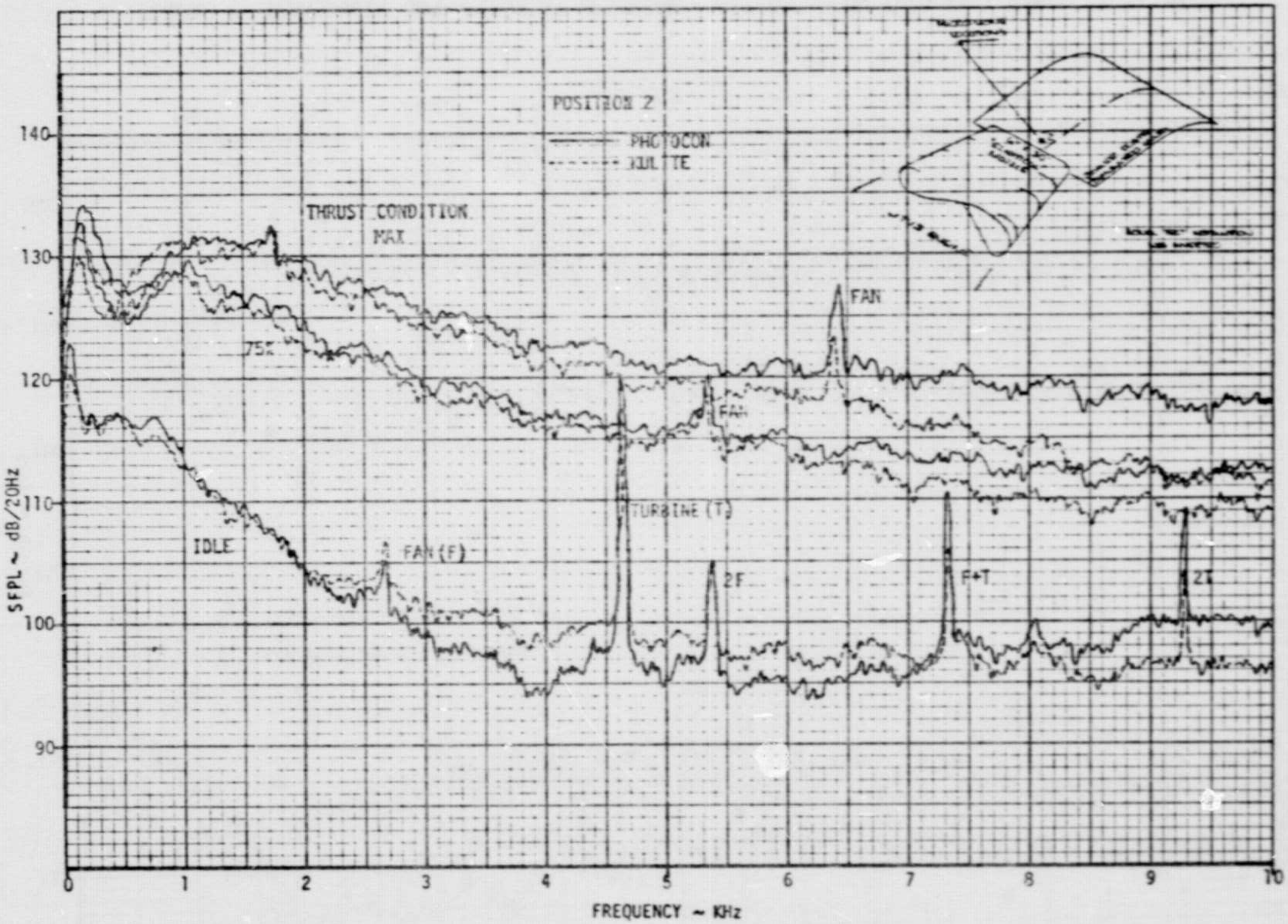


FIGURE 6 TRANSDUCER COMPARISON AT UPSTREAM POSITION (20 Hz BW)

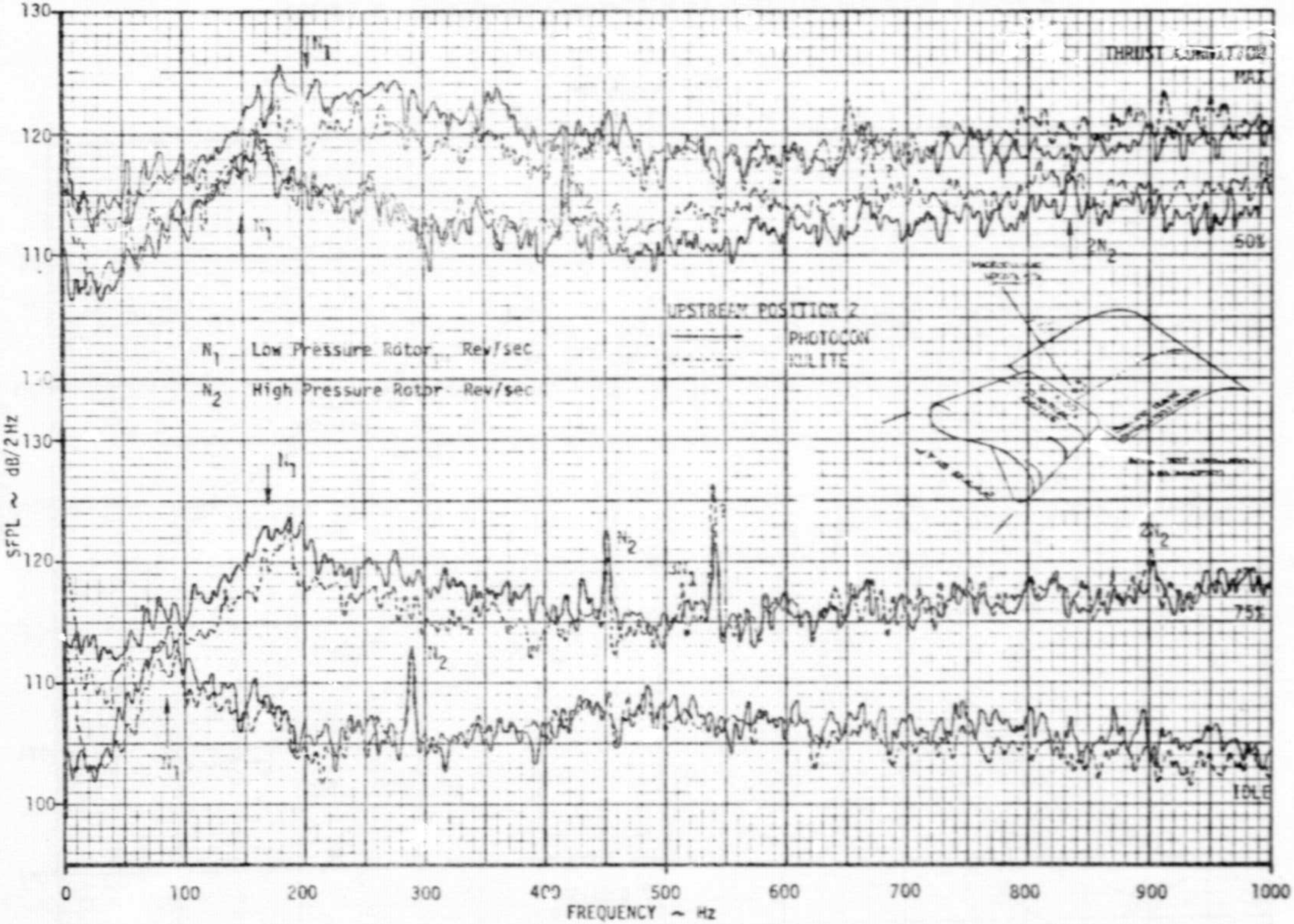


FIGURE 7 TRANSDUCER COMPARISON AT UPSTREAM POSITION LOW FREQUENCY RANGE (2 Hz BW)

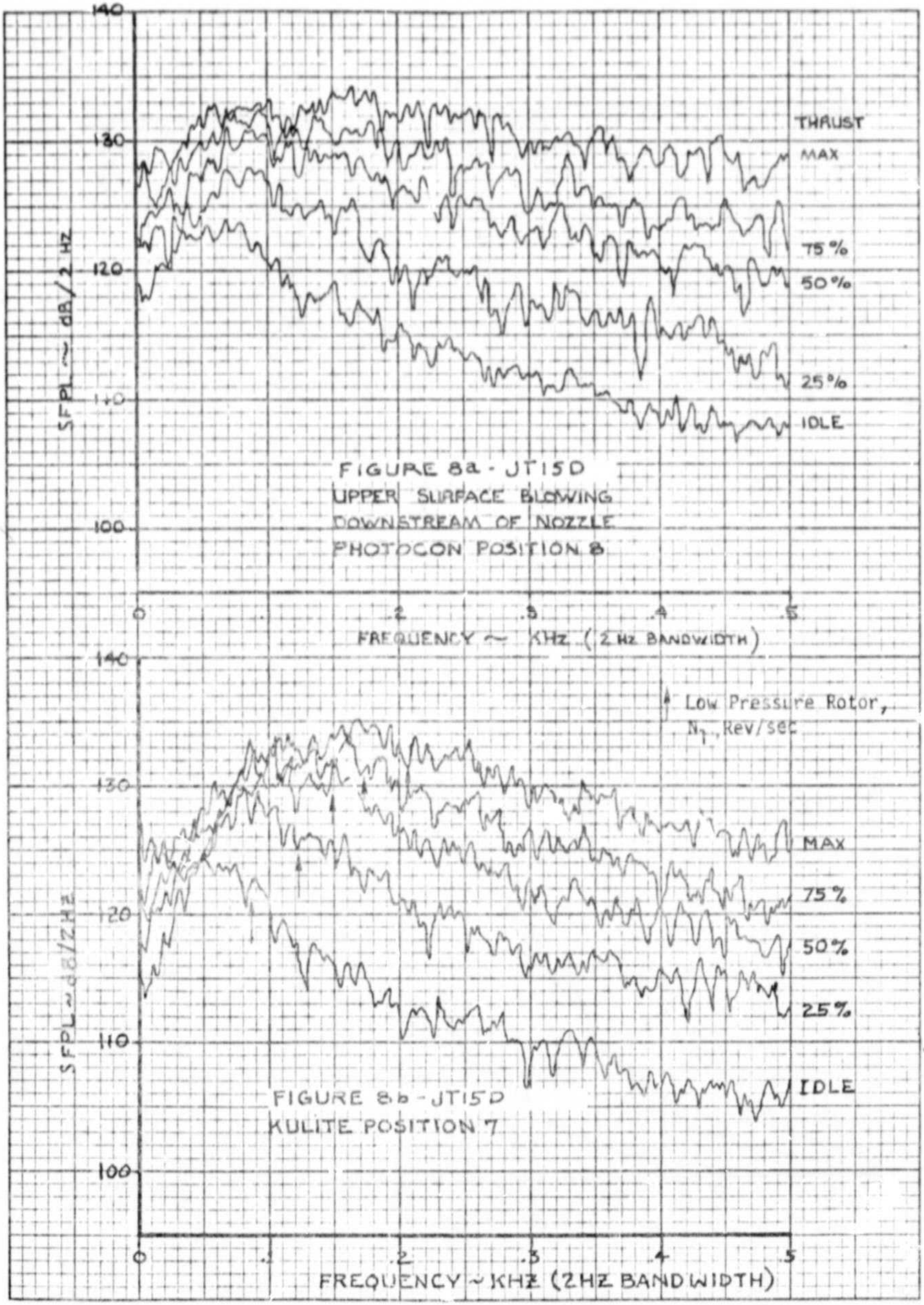


FIGURE 8 LOW FREQUENCY VARIATION WITH POWER SETTING

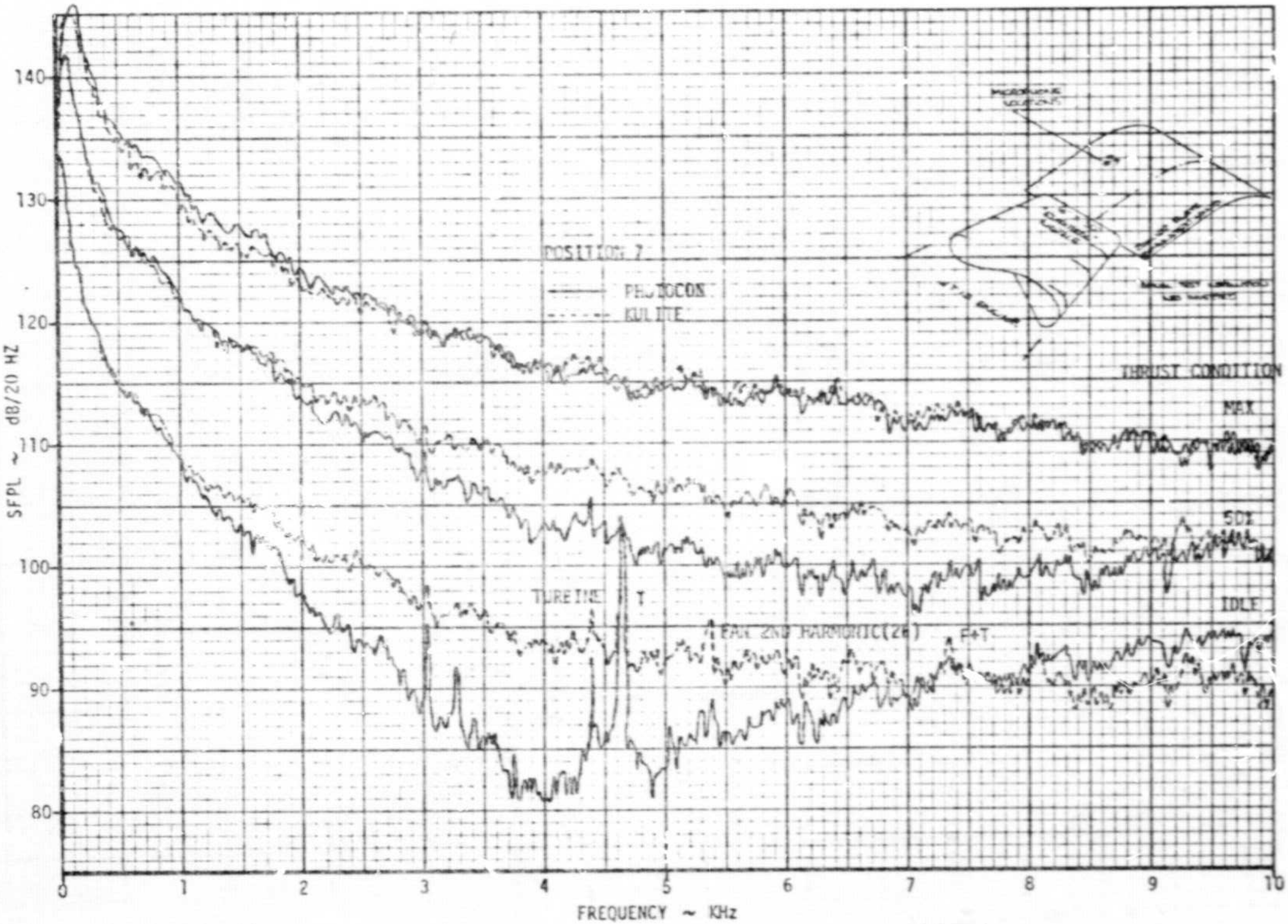


FIGURE 9a SPECTRAL LEVEL, UNCORRECTED, AT DOWNSTREAM LOCATIONS (20 Hz BW)

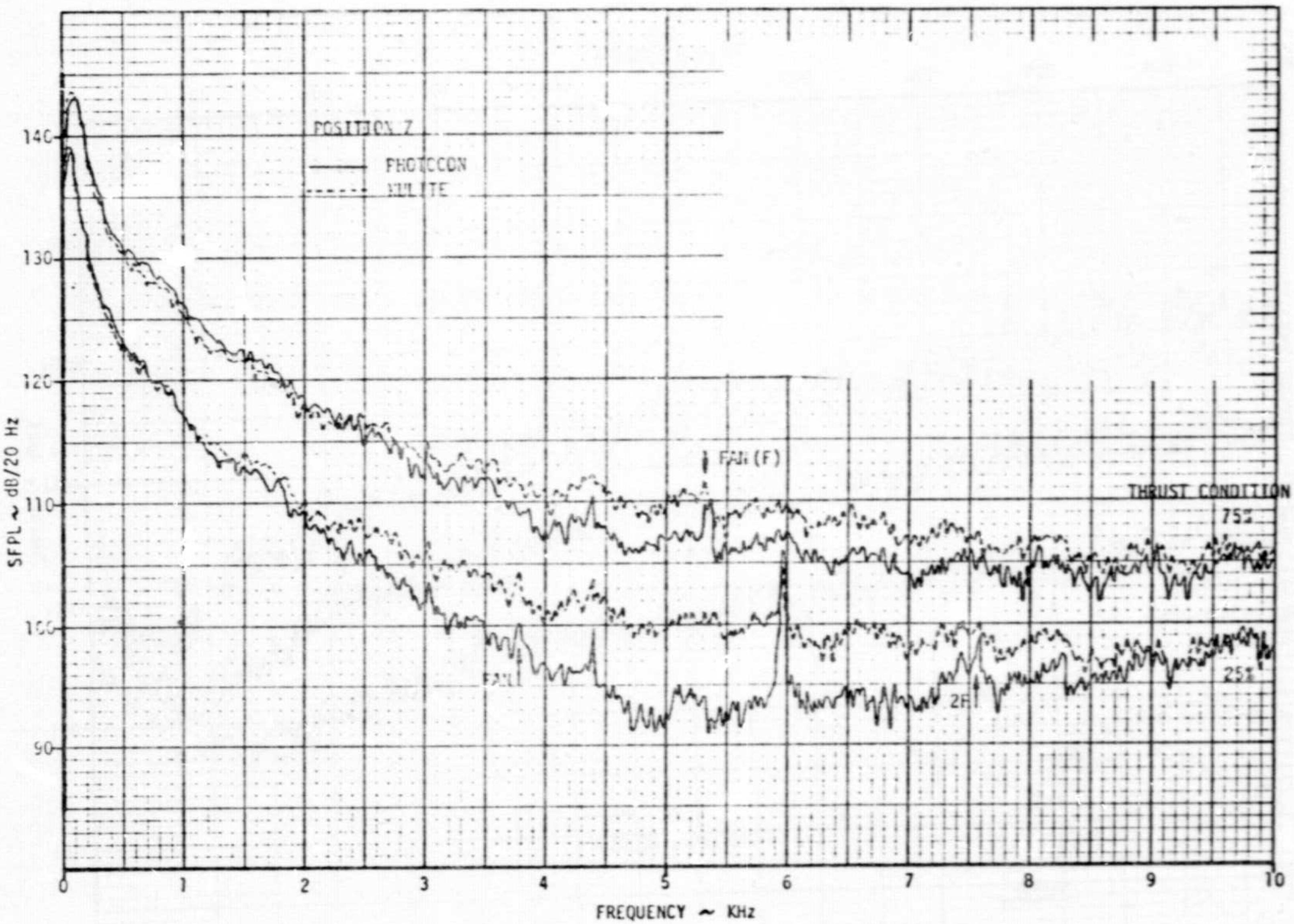


FIGURE 9b SPECTRAL LEVEL, UNCORRECTED AT DOWNSTREAM LOCATIONS (20 Hz BW)

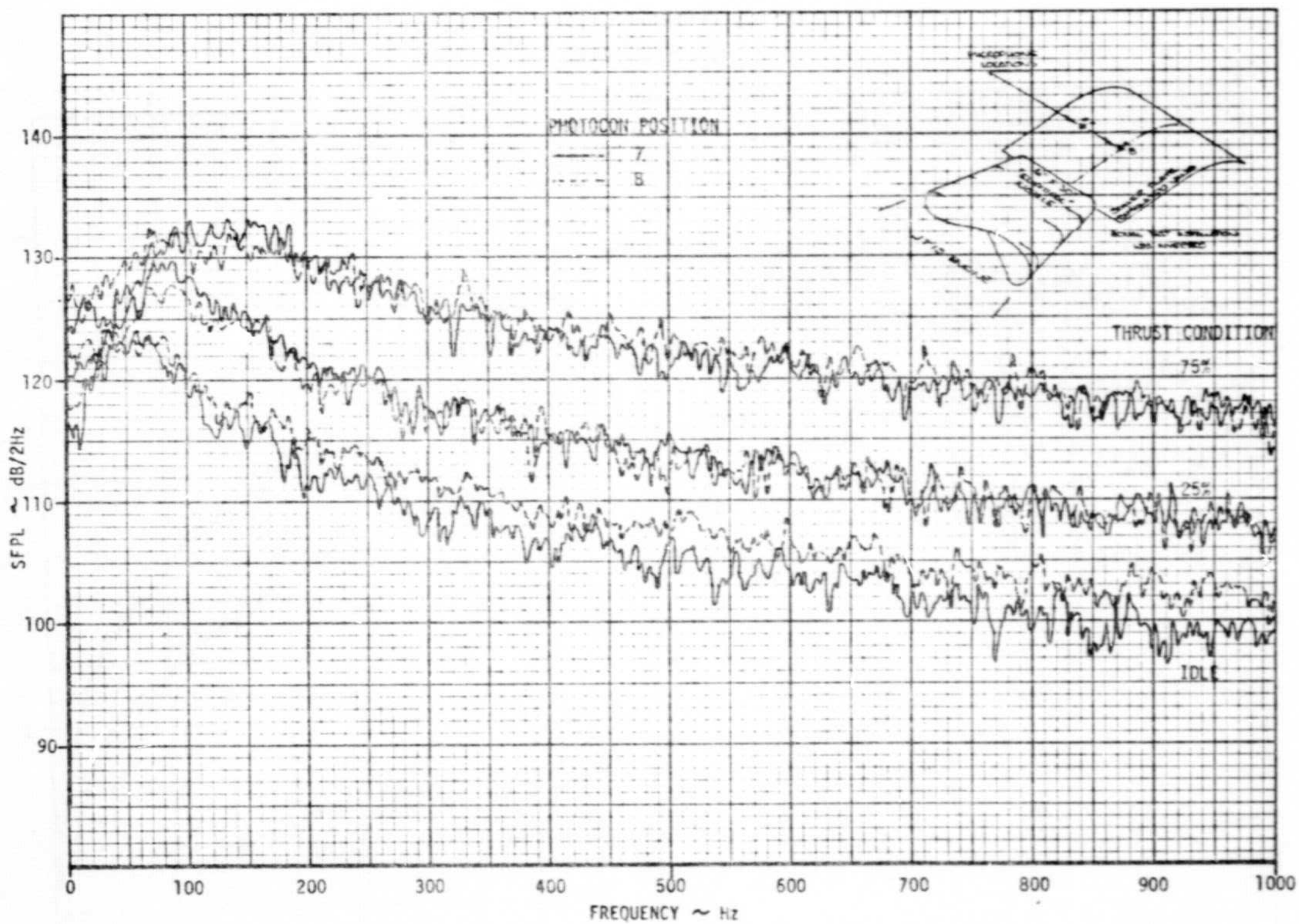


FIGURE 10 SIMILAR PHOTOCON SIGNALS AT DOWNSTREAM POSITIONS LOW FREQUENCY RANGE (2 Hz BW)

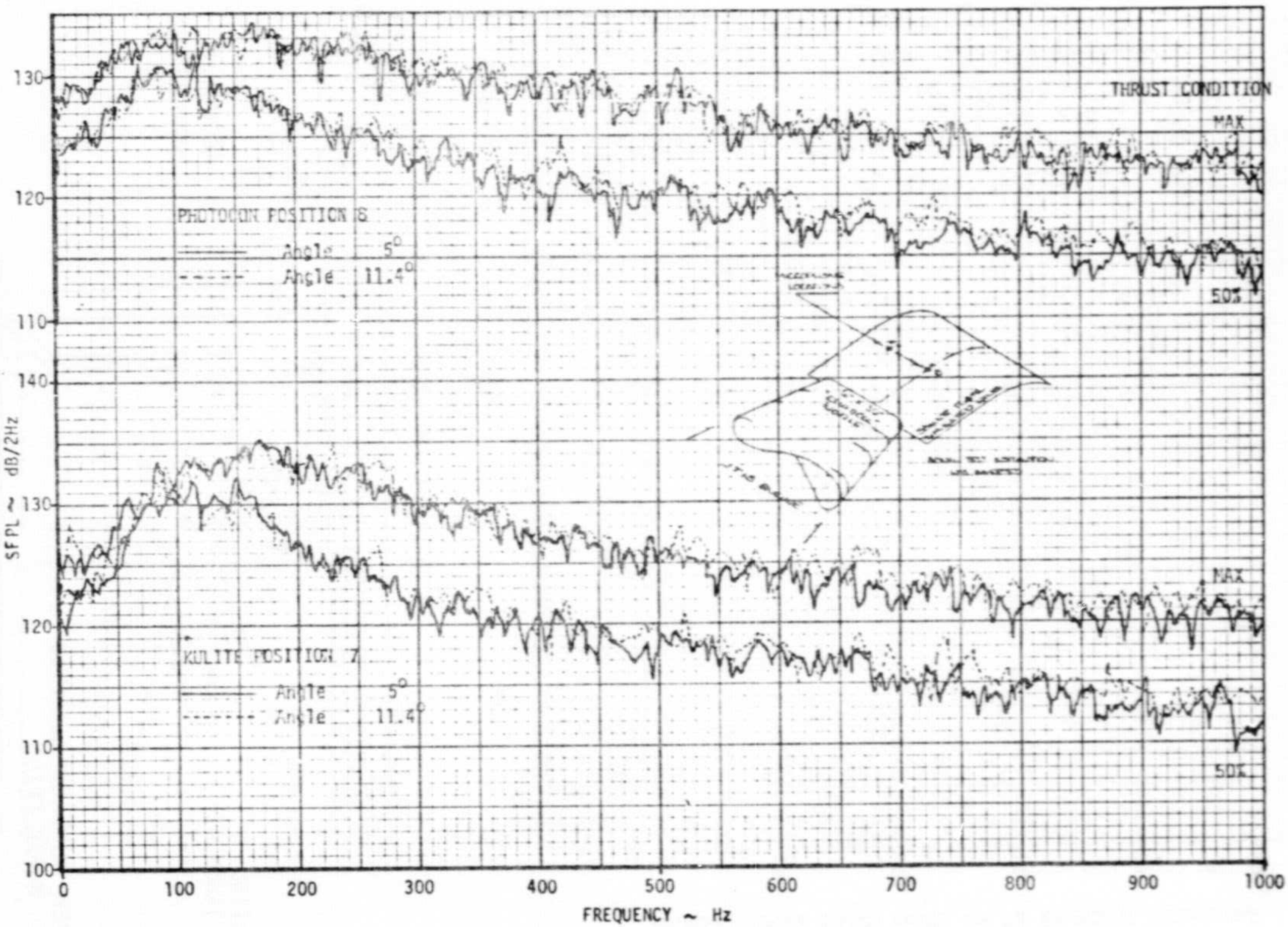


FIGURE 11 SMALL INFLUENCE OF IMPINGEMENT ANGLE LOW FREQUENCY RANGE (2 Hz BW)

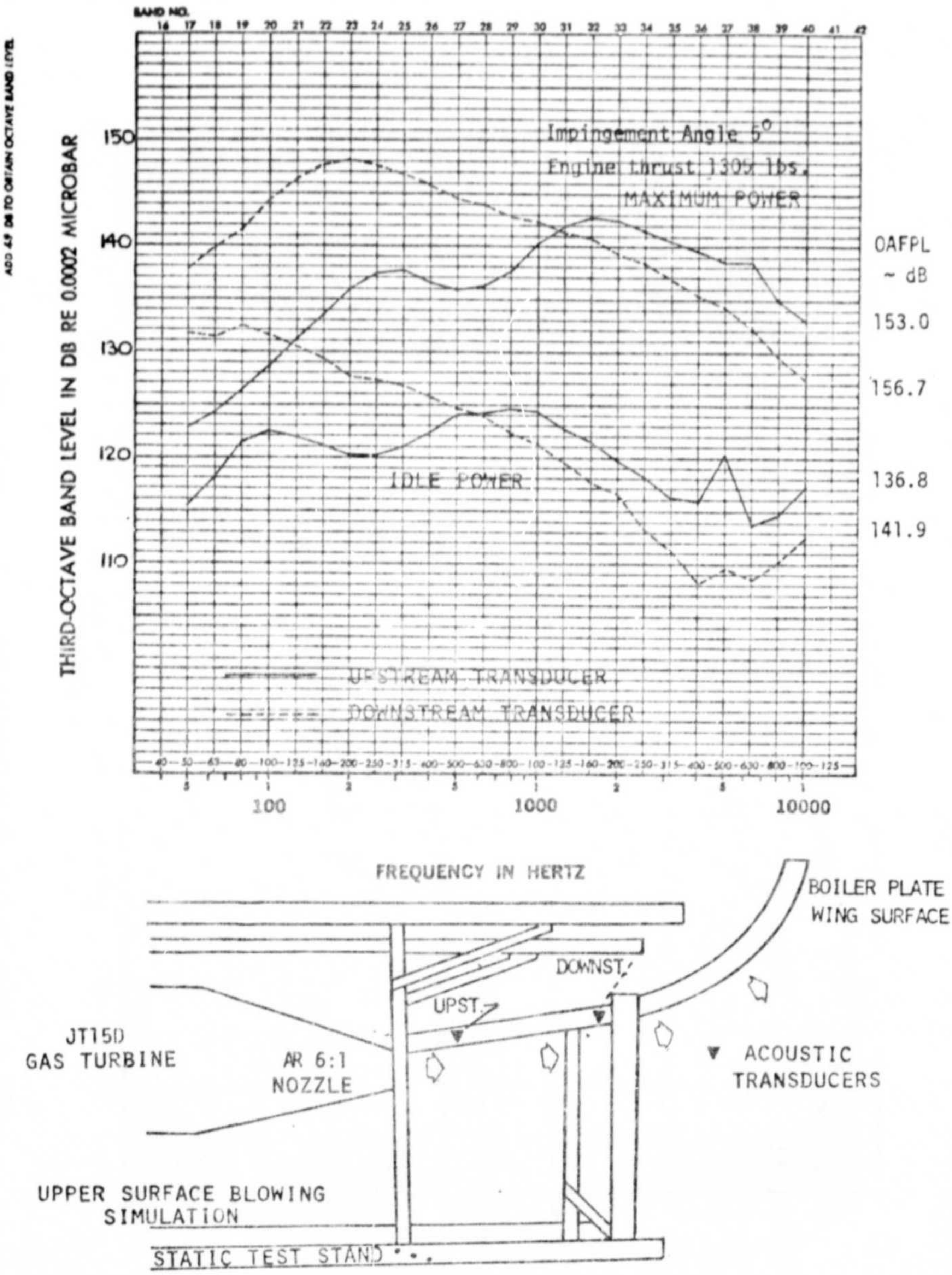


FIGURE 12 TYPICAL SPECTRAL RELATIONSHIPS IN UPPER SURFACE BLOWING

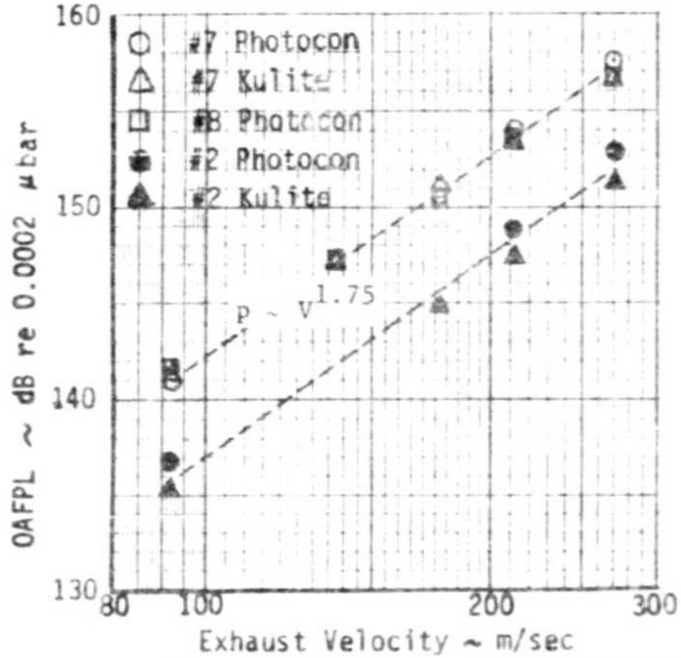


Figure 13a TRANSDUCER OVERALL FLUCTUATING PRESSURE LEVEL

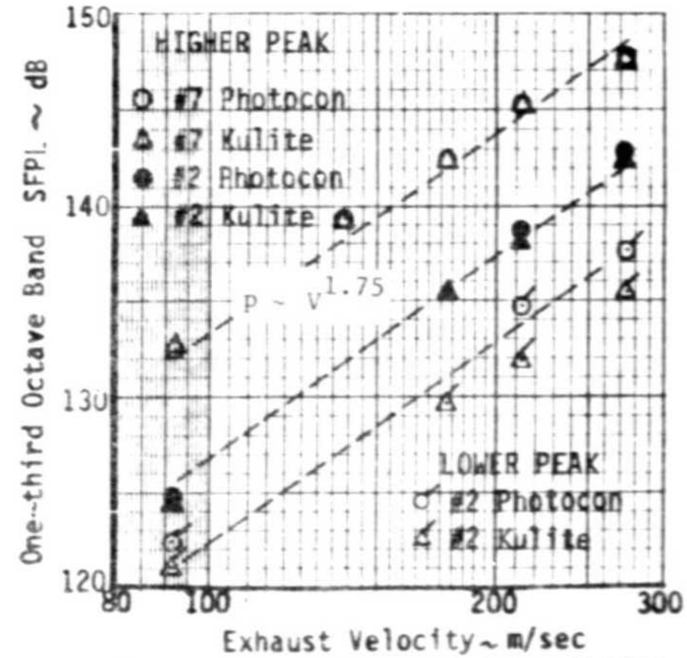


Figure 13b TRANSDUCER PEAK SPECTRA 1/3 O.B. SFPL

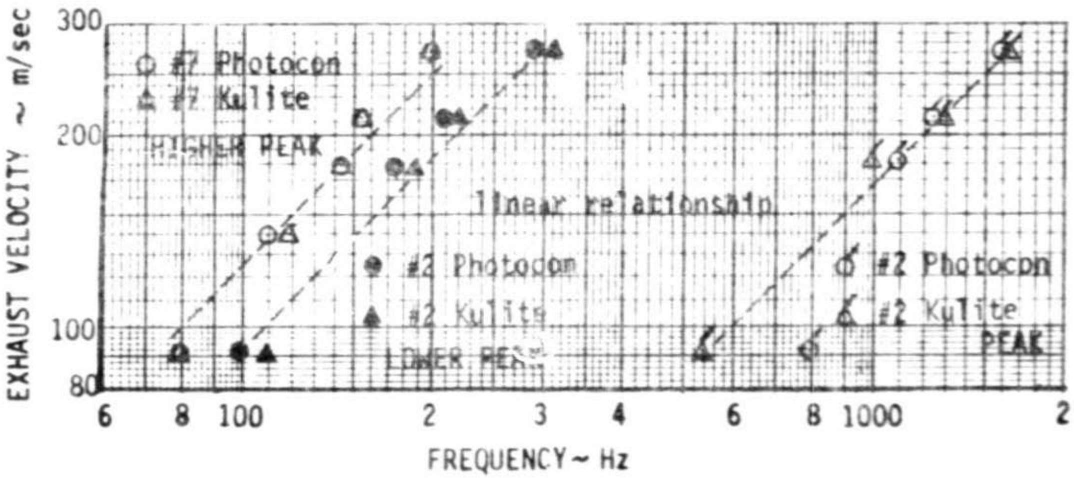
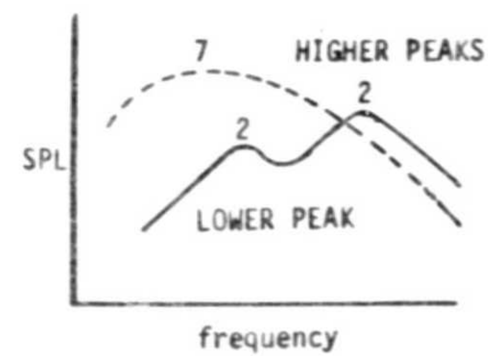


Figure 13c APPARENT PEAK FREQUENCIES



JT15D-USB STATIC TEST

FIGURE 13 SURFACE FLUCTUATING PRESSURE AND PEAK FREQUENCY RELATIONSHIPS WITH EXHAUST VELOCITY